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FACTORS DETERMINING THE LEVEL AND CHANGES IN INTRA-ARTICULAR PRESSURE IN THE KNEE JOINT OF THE DOG

BY SYDNEY NADE AND PETA J. NEWBOLD*

From the Department of Surgery (Orthopaedic Surgery), University of Western Australia, Queen Elizabeth II Medical Centre, Nedlands, Western Australia, 6009

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SUMMARY

1. Intra-articular pressure levels were determined for joint positions throughout the normal physiological range of movement of dogs' knee joints.
2. Change in joint position resulted in change in intra-articular pressure. It was demonstrated that intra-articular pressure is highest with the joint in the fully flexed position. Minimum pressure was recorded at a position between 80° and 120°. Minimum pressures were usually subatmospheric.
3. The rate of change of joint position affected intra-articular pressure.
4. The relationship of intra-articular pressure and joint position before and after full flexion demonstrated a hysteresis effect; the pressures were lower than for the same joint position before flexion.
5. Maintenance of the joint in the fully flexed position for *increasing* periods of time between *repeated* movement cycles resulted in a similar reduction, of constant magnitude, in pressure between joint positions before and after each period of flexion. However, there was also a progressive decrease in pressure for all joint angles over the total number of movement cycles.
6. There is a contribution to intra-articular pressure of joint capsular compliance and fluid movement into and out of the joint (both of which are time-dependent).
7. The recording of intra-articular pressure in conscious, upright dogs revealed similar pressure levels to those measured in anaesthetized supine dogs.
8. The major determinants of intra-articular pressure in normal dog knee joints include joint size, synovial fluid volume, position of joint, peri-articular tissue and joint anatomy, membrane permeability, capsular compliance, and movement of fluid into and out of the joint.

INTRODUCTION

Diseases of joints are common and there have been many investigations carried out on abnormal synovial joints. The physiology of normal knee joints, in comparison, has been relatively neglected. Jayson & Dixon (1970*a*), McCarty (1980) and Levick (1979*a*, *b*, 1980) have shown considerable interest in this subject. Production and regulation of synovial fluid within the joint cavity has been a prominent topic for study as its composition and volume is greatly affected by disease and trauma.

* Authors' names are in alphabetical order.

Joint fluid is essentially a dialysate of blood plasma with the addition of hyaluronic acid which is produced by synovial cells lining the joint cavity. The nature of this synovial fluid, and its volume, are maintained by the movement of fluid, virtually all trans-synovial, into and out of the joint (Simkin & Nilson, 1981). This movement is influenced by both hydrostatic and osmotic pressure gradients which exist between the capillaries, interstital space and synovial cavity (Levick, 1979*a*; McCarty, 1980).

The constant volume of fluid contained in a normal joint indicates a net balance of trans-synovial ingress and egress. When the joint is affected by either disease or trauma this balance is upset. There can be a change in the permeability of the synovium to the passage of fluid into and out of the joint, and there may also be increased intra-articular metabolic demands (McCarty, 1974; Niinikoski & Einola, 1977). Both of these states can result in changes in composition and volume of the synovial fluid (Ropes & Bauer, 1953; Yehia & Duncan, 1975). Changes in synovial fluid volume are reflected by changes in intra-articular hydrostatic pressure. It has been demonstrated in normal joints of humans and animals (Levick, 1979*a*; Jayson & Dixon, 1970*c*), that movement of the joint also causes changes in intra-articular pressure resulting in movement of fluid in and out of the joint, in addition to that which occurs as a result of the hydrostatic and osmotic pressure gradients in an immobilized joint (Levick, 1979*b*, 1980).

Intra-articular pressure and volume relationships in abnormal joints have also been investigated in man (Jayson & Dixon, 1970*a*, *b*, *c*) and animals (McCarty, Phelps & Pyenson, 1966), along with studies on joint effusions (Caughey & Bywaters, 1963; Eyring & Murray, 1964; Palmer & Myers, 1968), and capsular compliance (Myers & Palmer, 1972). In diseased and traumatized joints, the relationship between pressure and volume can change dramatically during the formation of an effusion, and this is to a large extent due to the visco-elastic properties of the joint capsular tissues and their response to the increase in joint fluid volume (Jayson & Dixon, 1970*a*; Myers & Palmer, 1972).

We felt that there was need for further investigation, in normal joints, into the relationships between intra-articular pressure and the position of a joint. We elected to use the knee joint of the dog in order to study intra-articular pressure, both in relation to static position of the joint, and the changes in pressure with movement of that joint.

METHODS

Anaesthesia was induced in mongrel dogs weighing 9–23 kg with pentobarbitone at a dose of about 30 mg kg^{-1} and maintained, using a CIG Midget 3 anaesthetic machine, by inhalation of an oxygen/nitrous oxide/halothane mixture for the duration of each experiment.

Right femoral arterial *blood pressure* was measured by cannulation and connexion to a physiological transducer (Statham Model P23DC). *Body temperature* was monitored by a rectal thermometer and maintained at 37–39 °C by means of a heated platform, augmented when necessary by a heated blanket.

Measurement and changes of joint position. Two bone screws were inserted about 4 cm apart in line with each other along the mid-shaft of each femur. The animal was placed in the supine position and secured firmly to the study table by fixing the bone screws to a metal scaffolding attached to the table. This method enabled each femur to be positioned vertically at a right angle to the dog's body. The heel tendons of the dog were placed on a horizontal bar which could be raised or lowered in order to change the angle of both legs with respect to the thighs. A pair of dividers was used to measure joint position by placing the axis over the mid point between the tibial and femoral condyles, just under the distal edge of the patella when the joint was at about 90° (Fig. 1). One arm of the dividers was then set in line with the two vertically placed screws in the femur, and the other placed parallel to the tibia.

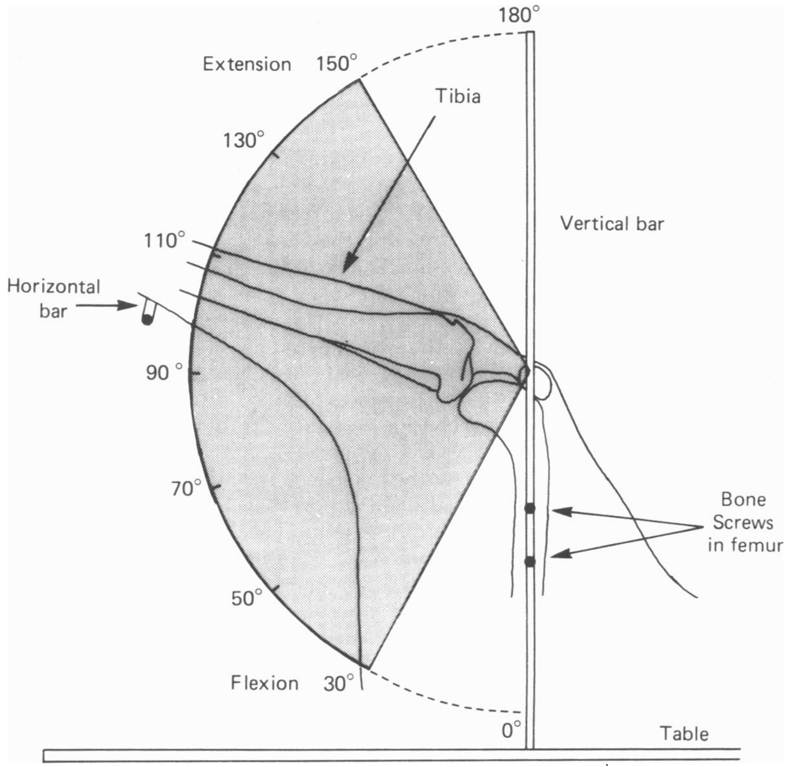

Fig. 1. Each animal was placed in the supine position with the two femoral screws attached to a vertical bar, while the tibia was rested over a horizontal bar. A standard centre-point, of best fit for the full range of movement, was selected and, using a goniometer and dividers, the angles were measured out in 10° steps. The shaded area represents the normal flexion–extension range for most dogs.

Positions of the joint, over the full range of natural movement of the dog's knee, were then marked on a chart attached to the scaffolding in 10° increments for each experimental animal. In this study with dogs the range was usually 30°–150°. This provided an accurate method of repeating measurements at the same angles throughout each experiment. Using the same horizontal bar beneath the heel tendons of the dog's legs, both knee joints could be moved in unison to the same position, and, by using two separate bars, they could be moved independently.

A measurement sequence, called a run, commenced at the 90° position. The knee joint under study was then moved in 10° increments to the fully flexed position, and then in the reverse direction to the fully extended position, and was finally returned to the 90° position. At each position the pressure recordings were taken for at least 2 min before movement to the next position.

In this study we report the results found from 14 normal dog knee joints.

Cannulation of the knee joint. A small skin incision of length 1·5 cm was made lateral to the mid portion of the patellar ligament. With the knee joint at an angle between 90° and 120°, an 18 gauge inextensible fluid-filled Teflon cannula, with small perforations around the tip, was inserted through the incision with its steel trocar. This allowed an easy and fast entry of the cannula into the joint space. A stop-cock, joined to the transducer via a fluid-filled tube, was in the open position so that immediately on withdrawal of the steel trocar, the cannula was connected and initial pressure measurements made. The angle of entry of the cannula was such that the multi-perforated tip slid up to rest inside the joint space, just beneath the patella, and free of the intra-articular fat pad. With the cannula positioned this way there was very little movement of the tissues over the cannula during movement of the joint. Radiographs taken at each 10° angle over the full range of movement demonstrated that there was no kinking of the cannula, and the tip and perforations remained within the joint. At the end of each experiment, dissection of the knee joint confirmed the correct position of the cannula tip. Using dyes in the injection fluid we verified that there was no leakage from the joint around the cannula, even under high intracapsular pressure produced by injection of large volumes of fluid into the joint. Cannulation of the knee joint was not always technically satisfactory. Animals which required multiple attempts of insertion, which had intra-articular bleeding, or were found to have the cannula tip incorrectly positioned, were excluded from the analysis of results.

Measurement of intra-articular pressure. The Teflon cannula was connected, via inextensible tubing filled with saline, to a physiological pressure transducer (Statham Model P23DC) which was positioned horizontally level with the knee joint. The transducer output was amplified and recorded through a Grass Model 7 pen recorder, following calibration against a mercury manometer. Base-line drift of the recorder was less than 2 mmHg hr^{-1}. This was monitored and corrected, when necessary, at regular intervals throughout the experiment.

Recordings in awake upright dogs. Recordings were also carried out in three awake dogs. In order to insert a cannula into the knee joint, anaesthesia was induced with a short-acting, intramuscular tranquillizer (acetyl promazine). A small incision was made through the skin on each side of the knee to be tested, using local anaesthesia (1 % lignocaine). With the joint at 120°, an 18 gauge Teflon cannula was carefully passed through the knee from lateral to medial side, just beneath the distal portion of the patella. The cannula had small perforations half-way down its two inch length, and was positioned such that these were within the joint. This was again verified by dissection at the conclusion of the experiment. The open end of the cannula on the medial side was heat-sealed and clamped to ensure that it did not change position and slide out of the knee. This cannula was connected to the pressure transducer and pen recorder for monitoring intra-articular pressure.

The anaesthetized animal was then lifted into a metal trolley and fitted into a specially made cloth hammock, which supported its head and body comfortably, while leaving its legs free, with the feet just touching the floor of the trolley. Once secured, the animal was allowed to regain consciousness while the position of the knee was measured, using dividers and a protractor, and the intra-articular pressure was monitored. When awake, the animal was able to stand and support its own weight. It could move its legs freely, but was restrained in a stationary upright position for the duration of the experiment. It was possible to record the pressure at several positions of the joint while the animal was under full or light anaesthesia in the upright position, and in the awake state with the joint fully loaded.

These experiments were done to confirm the validity of recordings made in the anaesthetized animal and were not prolonged, no animal being allowed to remain unanaesthetized for more than 15 min.

RESULTS

1. Intra-articular pressure following insertion of cannulae before joint movement. The insertion of the fluid-filled recording cannula into the joint usually took place at an angle of 90°. When the tip of the cannula entered the joint and was not obstructed by fat or other intracapsular tissues, the fluid in the cannula flowed spontaneously into the joint. A similar inflow had also been demonstrated in rabbits (Levick, 1979*a*). The cannula was immediately connected to the transducer.

This inflow of fluid could alter pressure/volume relationships in the knee by increasing, even by a very small amount, the volume of intra-articular fluid. At the time of first measurement of pressure following insertion of a cannula some seconds before, thirty-four of thirty-seven knees showed the pressure to be subatmospheric. The pressure on cannulation was -3.74 mmHg (S.E. of mean ± 0.51). The range of pressures recorded at this time varied between -11.0 and -1.0 mmHg. The intra-articular pressure was then monitored continuously for at least 20 min. Over the first 10 min the pressure increased to reach an almost steady state which was usually still subatmospheric. A more gradual rise in pressure over the next 10 min brought the average pressure to around zero. Although the initial more rapid rise in pressure may have been primarily due to equilibration of the joint with the fluid in the cannula (Levick, 1979*a*), the slower rise up to at least 20 min after cannulation may be explained by transudative or exudative fluid flow into the joint. This could be due either to slight irritation produced by cannulation, or to a slow net influx of fluid to the joint as a result of hydrostatic pressure differences set up by the immobility of the joint at 90° during the monitoring period after cannulation.

2. *The range of pressures measured*. Depending on the position of the knee joint, the lowest pressure recorded was −17 mmHg, and the highest was +50 mmHg. For any one knee joint, the position at which the minimum and maximum pressure was recorded remained constant. However, there was some variation between animals, and the actual angle measured in the fully flexed position was not the same in all dogs because of the various factors which determine range of joint movement from both intra- and extra-articular causes.

3. *Variation between animals*. Because mongrel dogs were used in this study, there was considerable variation in the size of the knee joint among animals. This made a difference in the absolute values of intra-articular pressure, particularly in the flexed position. Although the pattern of pressure changes in relation to joint position was the same for all animals, the absolute level of pressure recorded at any one joint position varied between animals. Therefore in demonstrating our results, we have decided to use examples from individual animals rather than mean values in most cases. This variation between animals was also found, in a study of dog's knee joints, by McCarty *et al.* (1966).

4. *Intra-articular pressure is not constant*. There is a change in intra-articular pressure with change in position of the knee joint. With change in position of the joint towards flexion, there was a rise in intra-articular pressure (Fig. 2). The maximum pressures were always generated in the fully flexed position. We did not generally find, as did Levick (1979*a*) in the rabbit's knee joint, a correlation between the minimum pressure level recorded in any joint and the maximum in that joint, in a different position. That is to say, joints with the lowest minimum pressures did not necessarily have the lowest maximum pressures. The correlation between the minimum pressure at 110°, and the maximum pressure at 30° flexion, was computed across the full set of data using the Pearson product–moment coefficient. This produced a coefficient of 0·389 ($P < 0{\cdot}05$). However, an inspection of the scatter diagram suggested that this may not be a valid conclusion, the numerical value of the relationship being strongly influenced by two outlier points, both from the same animal. Indeed, when the coefficient was re-computed without these two points, the value fell to 0·264 which does not approach statistical significance.

Fig. 3 shows the relationship between joint position and intra-articular pressure for different animals during a full 'run'. It is to be noted that the position at which minimum pressures were recorded were not at the extreme end of range of movement. Full passive extension of the knee joint resulted in an intra-articular pressure above the minimum. The minimum intra-articular pressure was recorded with joint position

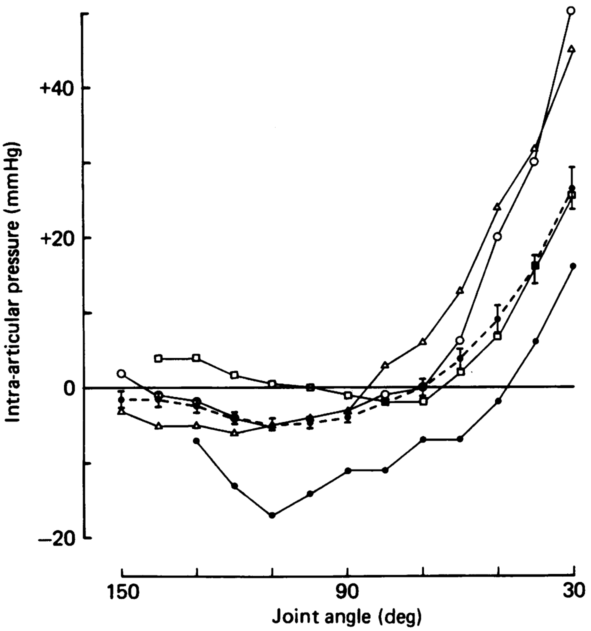

Fig. 2. The relationship between position of the joint and intra-articular pressure in normal joints. The continuous lines are measurements from four different dogs. The dashed line is the mean with standard errors from eighteen knee joints.

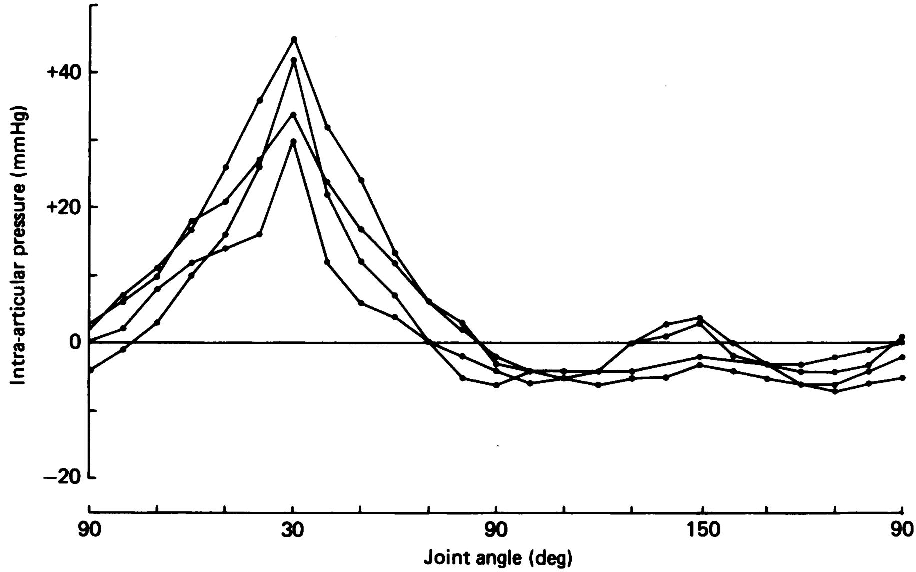

Fig. 3. Intra-articular pressures during flexion and extension 'runs' in four different dogs showing that subatmospheric pressures were recorded mostly between 80° and 120°. Pressures rose when the joint was further flexed or extended.

at an angle between 80° and 120°. Although there was variation in absolute pressure levels between animals, there was concordance in intra-articular pressure between both knees of the same dog. Fig. 4*A* is a direct recording of intra-articular pressure, while the knee joints were moved in unison, in a continuous position change rather than the usually employed stepwise change in 10° increments. Continuous repetitions of extension through flexion in one knee are demonstrated in Fig. 4*B*. Stepwise changes in position were reproducible on repeated intra-articular pressure measurements in any one dog.

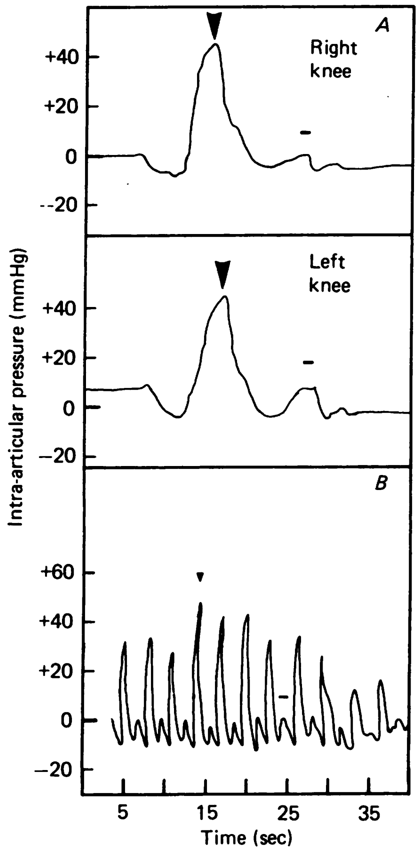

Fig. 4. *A*, direct recordings of intra-articular pressure taken from the right and left knees of the same animal during continuous and simultaneous movement through flexion and extension. (Arrowheads denote flexion, dashes denote extension.) *B*, direct recordings of intra-articular pressure from the one knee during multiple movements through flexion and extension. N.B. Recordings were made using a curvilinear pen recorder. The time scale is the same in *A* and *B*.

5. *The effect of maintaining the joint in a fully flexed position on intra-articular pressure.* Runs were carried out by initially moving the joint in 10° increments into flexion from the position at which the cannula had been inserted. It was observed that in any one joint the pressures for a given position were fairly constant on moving the joint to and from that position, except when the joint had been held in the fully flexed position between two recordings at a given position. A normal recording

sequence meant that the joint was held in the position of recording for 1–2 min before being moved to the next 10° incremental position. There was a difference in intra-articular pressure measured at any one position, depending on whether or not the joint had been through the fully flexed position during the sequence. If it had been held in the fully flexed position it was noted that the intra-articular pressure was lower than it had been for the same joint position before the 2 min period in full flexion.

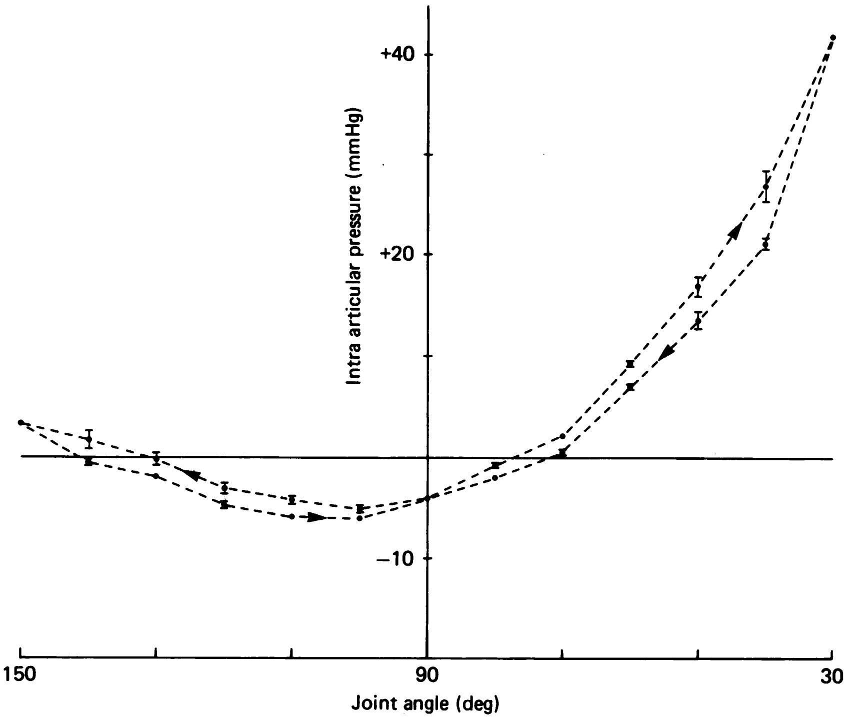

Fig. 5. Mean intra-articular pressures ±S.E. of means from three 'runs' on the same knee joint of one dog. This shows the difference in pressures at joint positions before and after maintenance of the fully flexed position. The arrows denote the direction of movement which took place in 10° steps commencing at 90° and moving towards flexion.

In Fig. 5 are plotted the mean intra-articular pressures and standard errors from three 'runs' on the same knee joint of one dog. This Figure shows the difference in pressures for joint positions before and after maintenance of the fully flexed position. It demonstrates a closed-cycle hysteresis effect and shows that by the time the joint has been back through full extension and returned to 90°, the pressure had returned almost to the original value measured before the run.

In most cases three to four 'runs' were carried out on each knee joint, and all 'runs' from all dogs showed this reduction in pressure after flexion, with the difference being greater for those joint positions nearest to full flexion. The magnitude of the reduction varied considerably between animals, and appeared to be greater in the knee joints of short thickset dogs than in the joints of tall lean dogs. The differences in pressure for joint positions before and after flexion, over the range of 40°–90°, were highly significant ($P < 0{\cdot}001$: paired t test). The mean of the differences ranged from 5·15 to 8·26 mmHg. Standard errors ranged from 0·426 to 0·706.

In order to obtain a clearer picture of the effects of forced flexion of the normal knee joint, further experiments were done. The joint was taken through multiple runs into and out of full flexion while measuring pressure at each of the 10° angle positions. The time allowed for measurement at each position was between 30 and 60 sec, while the position of full flexion was held for increasing periods of time with each consecutive run. Fig. 6 demonstrates that while the magnitude of the pressure reduction between joint positions before and after each full flexion remained constant, there was a progressive decrease in pressures recorded for all joint positions as the total amount of time that the joint had been held in full flexion increased.

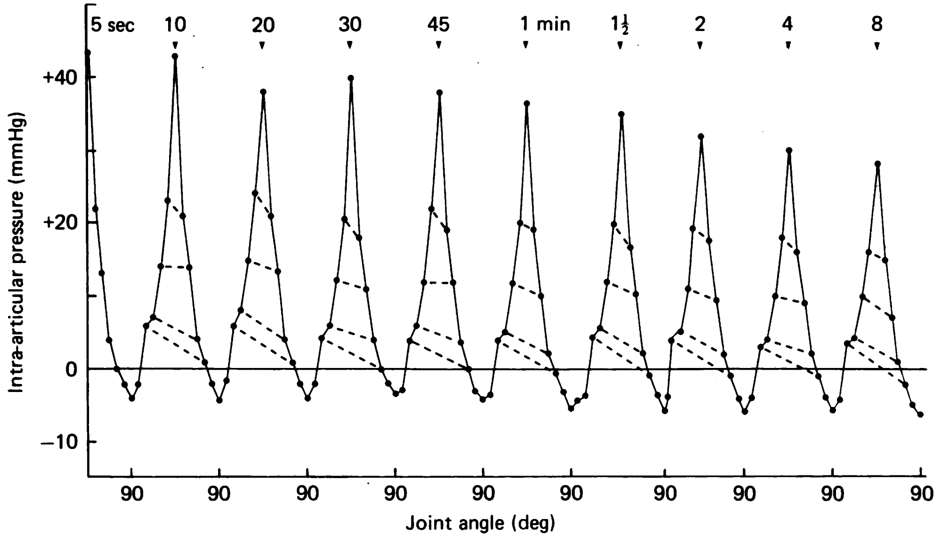

Fig. 6. Reduction of intra-articular pressure between joint positions before and after flexion during repeated 'runs' from 90° through 30°, and the over-all decline in pressures with the joint held for progressively longer periods in full flexion (30°). Numbers above arrowheads indicate duration of full flexion.

When the duration of maintenance of full flexion was kept at 1 min for each run, this progressive decrease in pressures for all joint positions was not seen, although the reduction in pressure between joint positions before and after flexion for each run still remained the same.

6. *The effect of rate of change of joint position on intra-articular pressure*. Normal runs were done with the knee joint held in position for up to 2 min while intra-articular pressure measurements were made and changes in position were incremental or decremental by 10°. That is to say, that a 50° change in position would normally have occupied about 10 min.

We noted that when the angle was changed directly from, say, 30° to 90°, without intermediate stops, the pressure at 90° was initially considerably lower than had been earlier recorded at that position. This pressure was usually subatmospheric. The intra-articular pressure then rose slowly and took several minutes to reach a constant level. Fig. 7 illustrates this phenomenon following rapid change of position.

This recovery of pressure at 90° was probably due, in part, to recovery of the capsular elastic tissues after being under tension during flexion. However, egress of fluid from the joint because of pressure differences in the more flexed position could also contribute to the observed intra-articular pressure. Levick (1979*a*) also observed a similar effect of lower pressure after acutely flexing the knee joint of a rabbit containing an increased volume of fluid.

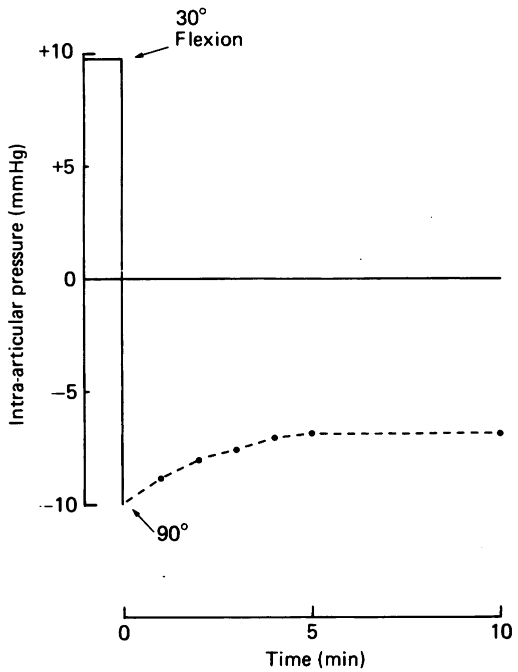

Fig. 7. Intra-articular pressure following rapid change of joint position from 30° (flexed) to 90° (semi-flexed) showing the time sequence of pressure change after the release from full flexion. The joint was held at 30° for 1 min before the rapid position change took place.

7. *Intra-articular pressure in lightly anaesthetized and awake animals.* In Fig. 8 is shown the intra-articular pressure in the knee of a dog after it had recovered from light anaesthesia to the point where it could stand and support its own weight. In the lightly anaesthetized phase, the pressures did not appear to be significantly different from those in the fully anaesthetized supine dogs. Measurements of joint position in these animals was less accurate than in anaesthetized dogs, with a variation from the stated position of $\pm 5°$. However, the positions of full flexion and full extension can be reliably compared. One difference to be considered in unanaesthetized animals is the ability to contract their muscles voluntarily. One of the dogs used for this study was of a breed that was able to hyper-extend the knee. This required active contraction of the quadriceps femoris muscle. It was interesting to note that this hyper-extended position was associated with a negative pressure of -24 mmHg, which is considerably lower than any of the minimum pressure recordings in anaesthetized animals. The effects of muscle contraction must also be considered as a determinant of intra-articular pressure. Jayson & Dixon (1970*c*) found that subatmospheric pressures were found in normal human knees during walking when the foot was down, the knee extended and the quadriceps muscle contracted.

They also found that the pressure in the normal human knee fell below atmospheric pressure by up to 30 mmHg during walking while the quadriceps was contracted.

Other than in the fully extended position of the knee joint, the differences in intra-articular pressure and joint position found in fully anaesthetized or awake animals do not appear to be significant.

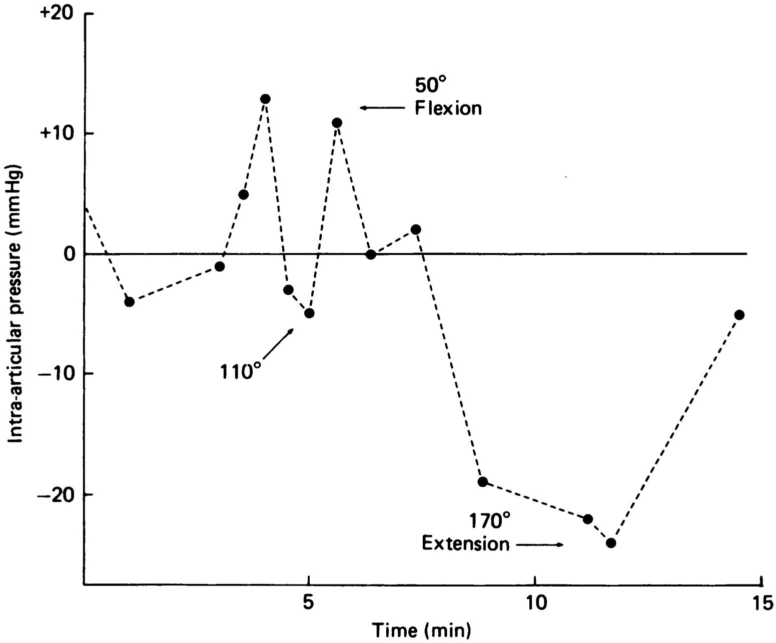

Fig. 8. Intra-articular pressure in the knee of a dog after it had recovered from anaesthesia to the fully-conscious state. The animal could stand and support its own weight and move its knee joint through a limited range. These intra-articular pressure levels, with the exception of the hyper-extended state (170°), were similar to those recorded from fully anaesthetized supine dogs.

We believe that further experimentation in the fully anaesthetized animal allows analysis of determinants of intra-articular pressure to be made with some confidence.

As well as attempting a comparison between fully anaesthetized and awake animals, we also continued to measure the relationship between intra-articular pressure and joint position in animals which had been used for the anaesthesia experiments after they had been killed by an overdose of anaesthetic agent. Obviously pressures could not be measured in these animals for very long after death, because of changing body temperature and muscle rigidity. For the short periods that recordings were done, the results were very similar to the observations in the alive anaesthetized animal.

DISCUSSION

The results of the present study confirm that intra-articular hydrostatic pressure is not constant. In normal joints, movement by its effect on intra-articular pressure, especially during flexion, influences the volume of the synovial fluid, and the compliance of the joint capsule.

Subatmospheric pressure. In normal physiological measurements it is now quite common to find pressures which are subatmospheric. Where they occur, for example in the interstitium, and the pleural cavity, they have a profound functional effect. Levick (1979*a*) found and discussed intra-articular subatmospheric pressure, and we have confirmed such pressure levels at certain knee joint positions. The level of subatmospheric pressure recorded by investigators has varied, as shown in Table 1.

TABLE 1. Sub-atmospheric pressure ranges found in the extended knee joint

Investigator	Subject	Approx. joint angle	Pressure range (mmHg)
Muller (1929)	Dog and man	Extended	−2·2 to −8·8
Reeves (1966)	Dog, cat, rabbit	Extended	−2·0 to −10
Jayson & Dixon (1970*c*)	Man	Extended	+2·2 to −1·5
Levick (1979*a*)	Rabbits	120°–150°	−8·8 to 0
Present study	Dogs	80°–120°	−17 to −1

Intra-articular pressure changes. Fluid movements occur in joints principally because of (a) the hydrostatic pressure differences across the capillary wall, interstitial space and synovial membrane, (b) the colloid osmotic gradients (between the joint cavity, interstitial space between the joint cavity and the capillary wall, and the blood within the capillary), and (c) movement of the joint. Although there is also some flow of fluid into the synovial lymphatics, it has been demonstrated in rabbits (Levick, 1980), that in the immobile joint this represents only a small fraction of total trans-synovial flow.

The highest pressure recorded from each animal in this study was with the joint at the most flexed position (+50 mmHg at 30° flexion). This pressure would favour egress of fluid from the joint, while positions with progressively lower intra-articular pressure would allow net ingress of fluid to the joint, due to greater hydrostatic pressure in the capillaries. At this point the resulting colloid osmotic gradient must play a significant role in counteracting this movement of fluid into the joint. That is to say, apart from a build-up of hydrostatic pressure due to intra-articular volume increase, an osmotic gradient would also be established and both of these forces would favour an egress of fluid. In the normal knee joint the pressure must be delicately maintained by these forces. In our studies we have found only small fluctuations in pressure, of 1–2 mmHg over several minutes, at any one joint position.

Rate of change of intra-articular pressure during change in position of joint. The rate of change of intra-articular pressure increased as the joint was moved towards flexion (Fig. 5). This is partially the result of anatomical features of the knee joint.

Because of the configuration of the joint capsule, and its relationship to the femur, tibia and surrounding joint tissues, during movement the shape of the capsule changes, especially when the joint is flexed. This was demonstrated by infusing the joint with radiopaque dye and taking radiographs with the joint at different positions. The inextensible ligaments and the attachment of the muscles by tendons in and around the joint limit the range of angles that can be attained by the joint.

Caughey & Bywaters (1963) found that when saline was infused into the joint there was an initial phase of passive filling of the synovial cavity when the compliance of the joint tissues was high, and the pressure rose slowly. There is then a second phase in which the capsule and ligaments begin to resist the distending force of the fluid and pressure rises more rapidly (Jayson, 1981; Myers & Palmer, 1972).

In the present study it is proposed that with the change in joint shape during movement of the joint towards flexion, initially there is passive unfolding of the joint capsule (slow pressure rise), until a point is reached at which the joint capsular walls begin to resist stretch (change in wall tension). It was around this point, in our study between 70° and 50° flexion, that the intra-articular pressure curve began to rise more steeply (see Fig. 2). The faster the joint was moved into flexion, the steeper the pressure curve became. This is, presumably, because the visco-elastic response of the joint capsule to stretch takes time and has not accommodated fast enough to this change in position. The effect can be seen to some extent when comparing *A* and *B* in Fig. 4.

At the time of cannulation of the knee joint, a small amount of fluid entered the joint as a result of the pressure differences between the surrounding atmosphere and the joint cavity. This addition of fluid to the joint caused a small initial increase in the intra-articular pressure. Data from pressure/angle experiments done after the infusion of physiological saline suggest that addition of fluid to the joint increases the slope of the pressure/angle curve going into flexion. However, the small volume of fluid entering the joint during cannulation might be absorbed, especially given that the pressures during movement were not recorded for at least 20 min after cannulation. Therefore the effect of this fluid on the pressure curve may be insignificant.

Effects of full flexion on intra-articular pressure. The fully flexed joint position, which was always within the normal physiological range for each animal, affected the pressure levels recorded at less flexed positions immediately after. Pressures measured when a joint was moved sequentially from any position to full flexion, full extension and back to the starting position reflected a hysteresis effect (Fig. 5) which was more pronounced if additional fluid was infused into the joint before flexion. This effect might be explained by (a) movement of synovial fluid out of the joint due to the high intra-articular pressure during flexion, leaving a smaller volume and, so, lower pressure after flexion, and/or (b) a transient deformation, in the form of stretching, of the joint tissues due to the flexion. This difference in pressures before and after flexion was highly statistically significant, and occurred irrespective of the weight and joint size of the animal.

In an attempt to determine the significance of these factors we analysed the results from further experiments carried out on the effects of flexion. In Fig. 6 the magnitude of the immediate reduction in pressure, between angles before and after each flexion, remained fairly constant and did not appear to be affected by length of time in flexion. Although fluid movement and tissue deformation were probably both occurring during flexion, the constancy of this immediate drop in pressure afterwards would seem to be due mainly to tissue distension. On the other hand, the progressive decrease in pressure with increase in time held in flexion, for all joint angles (Fig. 6), seems to reflect a gradual net fluid egress from the joint due to the high intra-articular pressures caused by flexion.

It is suggested that recovery from deformation of the joint capsular tissues, during these intervals between progressively longer periods of flexion, takes place more rapidly than the replacement of any net fluid loss during the same period. When the joint was held in flexion repeatedly for only 1 min periods, this over-all decrease in pressures did not occur, possibly because the time in flexion was not long enough to cause an over-all net loss of fluid.

Fig. 7 shows the time taken (5 min) for recovery of intra-articular pressure to a constant level after the joint had been held in flexion for a period of time, then moved directly to 90°. Recovery to the original pressure at 90°, before flexion, often took longer than 5 min. In the repeated 'runs' experiment, during the intervals between periods of flexion, the joint was usually back into the more flexed angles (higher pressures) within 5 min. This could have led to the net loss of fluid from the joint over all the runs, but the possibility of some more permanent distension of the tissues having progressively taken place cannot be ruled out. In abnormal joints with an effusion present, intra-articular pressures appear to be unusually low with respect to the volume of fluid which can be aspirated. In this case there is probably permanent tissue distension as a result of the constant tension on the joint walls, created by the large volume of fluid (Jayson & Dixon, 1970*a*).

Distinguishing between movement of synovial fluid into and out of the joint, and compliance of the joint capsule, from changes in intra-articular pressure, is difficult. Levick (1979*a*) demonstrated a difference in recovery rates of intra-articular pressure during flexion after infusion of saline and then paraffin. As paraffin is unable to leave the joint, the difference between the two recovery curves gives some indication of the degree of joint compliance in relation to fluid efflux during flexion.

Still further studies of pressure–volume relationships in normal joints, using fluids with varying degrees of synovial membrane permeability, seem to be warranted. In addition, an investigation into the time factors involved in normal joints, in change in compliance of the joint capsule during periods of high intra-articular pressure, due either to maintained flexion of fluid effusions, could provide valuable information regarding the effects of joint disease or joint trauma.

The relevance of using anaesthetized animals. We felt it was very important to determine the comparability of the levels of pressures recorded in the fully anaesthetized animals to the fully conscious and upright animal. The results of these experiments, along with the lack of significant change (drop) in intra-articular pressures after death of the animal provides a valid basis for using fully anaesthetized animals in future experiments.

Consequences of changes in intra-articular pressure on joint physiology. One of the major determinants of intra-articular pressure, position of the joint, has been investigated in this study, while several more have been inferred. These include the size of the joint, capsular compliance, the volume of contained synovial fluid, net movement of fluid across the membranes between the capillaries and joint cavity, permeability of the membranes, the effects of periarticular tissue, and joint anatomy.

The changes in intra-articular pressure during movement of the normal joint have highlighted two important components of joint physiology; fluid movement across the synovium, and capsular stretch or compliance. It has been shown that movement of a joint, like the knee, has considerable influence on the pressure of the synovial fluid inside the joint. The range of pressures during flexion and extension of the joint are such that they exceed the articular hydrostatic pressures and drop well below the atmospheric pressure. Because of the properties of the synovium and synovial fluid, these pressures, which change so rapidly during movement, must play a direct role in maintaining a constant balance between synovial fluid volume and capsular compliance. Indirectly, they probably play an important part in maintaining the integrity of joint tissues such as the articular cartilage, and in providing an environment conducive to optimal use with low wear and tear in an active joint such as the knee.

The need to define normal joint function should lead to further studies being carried out on the permeability of the synovium and the degree of elasticity of the synovium and capsular tissues, as it is known that disease and trauma can change the properties and functions of both, and that this change in turn affects the nutritional and lubricational aspects of joint physiology.

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